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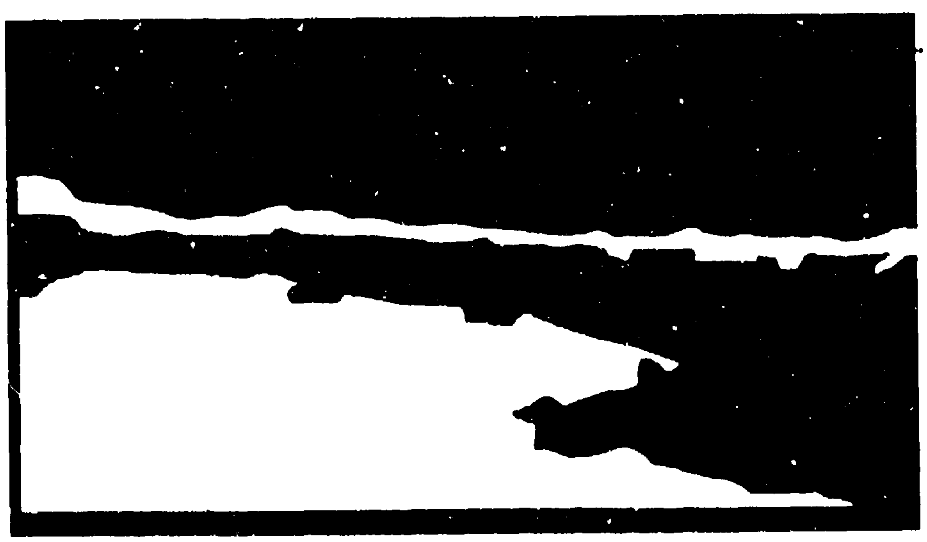

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A VARIABLE-FIELD PERMANENT-MAGNET DIPOLE FOR ACCELERATORS*

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Abstract

A new concept for a variable-field permanent-magnet dipole has been developed and fabricated at Los Alamos. The application requires an extremely uniform dipole field in the magnet aperture and precision variability over a large operating range. An iron-core permanent-magnet design using a shunt that was specially shaped to vary the field in a precise and reproducible fashion with shunt position. The key to this design is in the shape of the shunt. The field as a function of shunt position is very linear from 90% of the maximum field to 20% of the minimum field. The shaped shunt also results in a small maximum magnetic force attracting the shunt to the yoke allowing a simple mechanical design. Calculated and measured results agree well for the magnet.

Introduction

Requirements for the Advanced Free Electron Laser (AFEL) project at Los Alamos National Laboratory beam transport optics included that numerous magnetic and diagnostic elements be placed in a severely space-constrained area.[1] Furthermore, very high quality magnets were needed to maintain beam emittance. It was determined early that using electromagnets was not feasible because the coils would occupy too much space along the beam line. Space away from the beam line was less constrained and thus variable-field permanent-magnets (VFPMs) were suggested for this application. Variable-Field Permanent-Magnet Quadrupole (VFPMQ) magnets using a modification of the design first proposed by Halbach[2] were fabricated for this effort. These magnets satisfied both the minimum beam line space criteria because no coils are required, and the high field quality because iron poles are used to precisely shape the fields.[3] The primary modifications to the VFPMQ are that they were built as doublets and the field strength could be tuned over an extremely large range. To date, no VFPM dipole (VFPMD) has been fabricated that meets the high-field-strength and high-field-quality required in this application.

It is most economical and technically easiest to meet both the high-field-quality and the field-strength needed for the AFEL application with an iron-pole device.[3] The simplest method used to vary an iron-pole permanent-magnet device is to use a shunt, however, typical shunts result in extremely non-linear variations of field strength with shunt position, large forces between the magnet and the shunt, and irreproducible variation of the field with shunt position. We designed a permanent-magnet dipole in which the field strength in the aperture is varied by a specially shaped shunt that solves the problems of the "traditional" shunt.

Design, Fabrication & Measurement

The design of this magnet was broken into two steps. A coil-replacement permanent-magnet sector dipole was designed with an integrated field strength somewhat greater than required for the AFEL project. Pole shape was optimized using the FLUX-2D[4] code and standard design techniques for iron-pole magnets. After the "core" of the magnet was designed, a specially shaped shunt was designed. Traditional flat shunts suffer from a very gradual onset of shunting flux away from the aperture until the distance between the shunt and magnet is approximately the size of the aperture. Thereafter, flux diverted away from the aperture increases rapidly as the shunt is moved only a small distance closer to the magnet until very little flux remains in the aperture. The traditional shunt is, in practice, difficult to control with sufficient precision to accurately and reproducibly control the flux density in the aperture of the magnet of a VFPMD. We have designed a shunt that significantly extends the distance over which the shunt must be moved to alter the flux density in the magnet aperture. This not only relaxes the precision with which the shunt must be moved, but also reduces the magnetic force on the shunt which in turn reduces the structural requirements for the shunt hardware.

Figure 1 shows a schematic cross section of the magnet and shunt designed for the AFEL. The poles are shown on the left with the permanent-magnet material indicated by blocks with heavy arrows indicating orientation of the magnetization vector. The shunt is on the right shown in the fully engaged position (solid outline) and a nearly disengaged position (dashed outline). A motor package, including gear reduction and encoder units, is mounted to the right. All linkages in the shunt drive-train are designed for minimum backlash, however this is not strictly required since the force from the shunt is always applied in one direction, preloading the gears and preventing backlash. Limit switches at the minimum and maximum shunt positions both protect the magnet from damage and provide absolute reference for shunt position. The shunt position is redundantly determined by the encoder position readback

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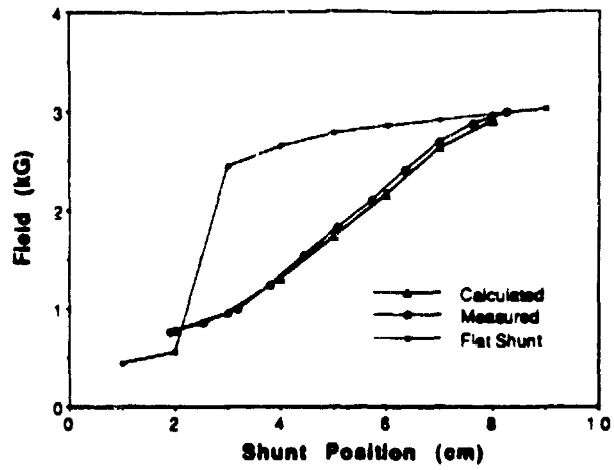

Fig. 1 Schematic cross section of the Variable-Field Permanent-Magnet Dipole used in the AFEL.

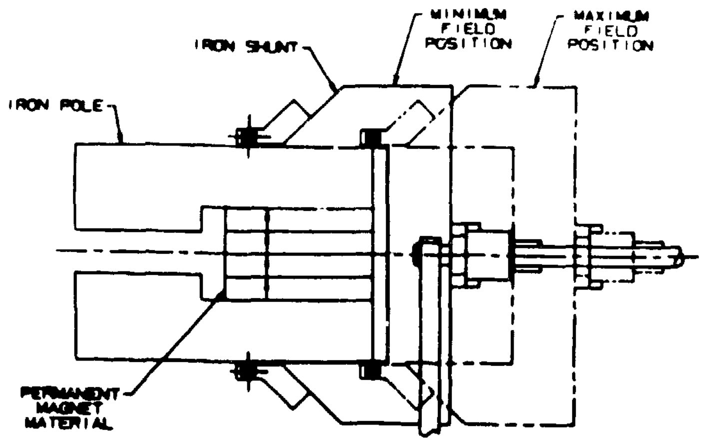

Fig. 2 Calculated and measured flux density plotted as a function of shunt position.

and the motor step count, each referenced to the maximum field limit switch.

The specialized shape of the shunt causes the leading "fingers" of the shunt to rapidly saturate as they approach the core yoke limiting the flux being diverted away from the aperture. As the shunt is moved further onto the yoke, the cross section of the fingers increase allowing more flux to be diverted through the shunt. It should become obvious that the taper of the fingers can be tuned to increase or decrease the amount of travel desired in the shunt for a given change in the flux density in the aperture. The taper chosen for the VFPMD magnets used in the AFEL project was a simple slope resulting in a nearly linear dependence of the flux density in the aperture on the shunt position over most of the tuning range.

Figure 2 shows the flux density in the aperture as a function of the shunt position, the flux-tuning curve, as calculated by FLUX-2D (the dashed line) and as measured (solid line) for the magnets fabricated for the AFEL project. The calculated flux-tuning curve is normalized to the data at the low-field point to account for 3-D effects not included in the calculation. The flux-tuning curve for a traditional shunt is also plotted in Fig. 2 illustrating the greatly extended position range and improved linearity of the flux-tuning curve for the modified shunt. The shape of the shunt fingers can be further refined such that the linear region of the flux-tuning curve can be extended over at least 95% of the entire range, however, this would result in greater fabrication costs for the magnet.

The range of flux densities delivered by the magnets described here varied from a minimum of 0 G, limited primarily by the magnetic remanence of the iron, to a maximum of 3.7 kG. Flux density measurements were found to be reproducible to better than 0.1% for a given shunt position, as determined by counting motor steps from the maximum flux-density limit switch.

Conclusion

Four VFPMD magnets were fabricated and characterized according to the design discussed above. These magnets have been installed and are currently in use in the electron-beam transport line of the AFEL project at Los Alamos National Laboratory. The design minimizes the real estate along the beam line occupied by the magnet while delivering a high-quality dipole field over a large tuning range, and reproducible to better than 0.1%. The fabrication cost for these magnets was approximately 20% less than anticipated for equivalent electromagnets and power supplies with none of the operational costs associated with electromagnets. Furthermore, these magnets can be used in applications where "fail-safe" operation is required. A motor shaft brake is removed only when current is applied to the motor preventing any motion of the shunt in the absence of motor current.

References

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[4] Vector Fields, Ltd., Oxford, England, (copyright 1981)